

RESEARCH MEMORANDUM

EFFECT OF FUEL-AIR DISTRIBUTION ON PERFORMANCE OF

A 16-INCH RAM-JET ENGINE

By A. J. Cervenka and E. E. Dangle

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

The effect of combustion on diffusion in the fuel preparation zone of a 16-inch ram-jet engine was determined. The eddy diffusion coefficients were found to vary from 0.6 square foot per second for no burning in the engine to 1.6 square feet per second with burning.

This information was applied in the design of a combustor to operate at lean fuel-air ratios. Operation to a lean fuel-air ratio limit of 0.007 was accomplished with the use of a cylindrical sleeve which limited fuel-air mixing upstream of the flame holder.

INTRODUCTION

This experimental investigation is part of a programmatic research on combustor design at the NACA Lewis laboratory. The end objective is to establish designs along with design criteria that will permit efficient and stable ram-jet combustion over wide ranges of fuel-air ratios and inlet conditions. This investigation and other initial studies of the program were conducted with simple V-gutter flame-holder designs.

Several investigators have reported on the operational characteristics of the V-gutter flame holder (references 1 to 3). These studies demonstrate that fuel distribution exerts an important influence on combustor performance. At lean over-all fuel-air ratios, the fuel distribution was found to have a greater effect than that of flame-holder geometry upon combustor performance (reference 2).

A useful mathematical approach describing the fuel distribution obtained with various fuel injection systems is presented in reference 4. With this method it is possible to predict the fuel-air pattern for various types of fuel injectors or for different locations downstream of the injector, once the stream diffusion coefficient for a particular type of injector is established experimentally. To apply this method to the

determination of the fuel-air pattern at the flame holder, however, the stream conditions must be the same as those under which the diffusion coefficient was evaluated. A diffusion coefficient determined with no burning in the engine would therefore be inadequate for use in predicting the fuel-air distribution at the flame holder with burning, since burning will introduce perturbations in the air stream into which the fuel is spreading.

The primary objective of this report is, therefore, to determine the effect of combustion on the diffusion coefficient in the fuel preparation zone and to design, with the aid of this information, a combustor which will provide the fuel-air distribution necessary for efficient combustion at lean fuel-air ratios.

The secondary objective is to determine the effects of flame-holder geometry upon combustion efficiency at simulated high flight Mach numbers.

APPARATUS

The test vehicle for this investigation was a 16-inch ram-jet engine. Installation of the test unit is shown in figure 1. The engine received its air supply from the laboratory combustion air system and then exhausted through a muffler to the atmosphere. Air flow to the ram-jet engine was controlled with a butterfly valve upstream of the test unit and was metered with an orifice system located in the supply line. The inlet air temperature to the ram-jet engine was maintained at approximately 600° F; heating of the air was accomplished, with no contamination, by a gas-fired heat exchanger.

The engine-outlet temperatures were obtained by a heat balance. The calorimeter consisted of a multiple water spray ring located 6 inches downstream of the engine exhaust nozzle and a thermocouple station 20 feet downstream of the water sprays. An insulated pipe, 24 inches in diameter and 22 feet long, made up the calorimeter portion of the test rig. The resulting gas and steam temperatures at the outlet of the calorimeter were measured by 16 thermocouples located in equal areas across the 24-inch-diameter duct.

Ram-jet engine. - The 16-inch ram-jet engine (fig. 2) used in this investigation was composed of a subsonic annular diffuser, a water-cooled combustion chamber 16 inches in diameter, and a water-cooled, fixed-area, converging exhaust nozzle.

The over-all length of the engine from the inlet of the subsonic portion of the diffuser to the nozzle outlet was 175 inches, of which the combustion chamber and nozzle length is 90 inches. The diffuser

centerbody extended from the engine inlet lip and terminated at the combustion-chamber inlet with a pilot burner on the downstream end. The centerbody was held in place by supporting struts whose maximum thicknesses were 17 percent of the chord length.

Pilot system. - A vortex pilot was housed in the downstream end of the centerbody. The pilot combustion chamber consisted of a truncated cone 10.3 inches long that changed in diameter from $7\frac{1}{4}$ inches at the upstream end to 6 inches at the exit. Propylene oxide in amounts not exceeding 5 percent of the total fuel flow was burned in the pilot. A single fuel nozzle rated at 21.5 gallons per hour at a pressure differential of 100 pounds per square inch was used. Air was scooped from the main air supply at two of the three main centerbody supports and ducted into the pilot through elbows which imparted a vortex action to the air. The fuel was ignited with a commercial jet-engine spark plug.

Fuel injector system. - The fuel injectors were located 20 inches upstream of the flame holder. Four fuel tubes entered the engine through the outer wall and each supplied a quadrant injector consisting of four modified commercial spray nozzles. The injectors could be moved radially between the outer wall and the inner diffuser wall.

The nozzles, rated at 21.5 gallons per hour at a differential pressure of 100 pounds per square inch, were commercial nozzles which were modified to reduce the external cross-sectional area without affecting the spray pattern. The fuel was sprayed upstream.

Fuel. - The physical properties of JP-3 fuel, used as primary engine fuel, are given in table I.

Flame holders. - The flame holders used in this investigation are shown in figure 3. Configuration A, a grid-type V-gutter flame holder with a blocked area of 54 percent, is shown in figure 3(a). Configuration B, an immersed-surface flame holder with a blocked area of 37 percent, is shown in figure 3(b). The immersed-surface flame holder consisted of Inconel plates arranged downstream of each other in such a manner that each succeeding plate would be bathed by the flame from the upstream plate and thus operate at a very high temperature. Configuration C, consisting of radial V-gutters with a blocked area of 37 percent, is shown in figure 3(c). Configuration A measured $1\frac{1}{4}$ inches across the open end of the V-gutter whereas configurations B and C measured $1\frac{1}{2}$ inches across the open end.

Control sleeve. - For one phase of the investigation a fuel-mixing control sleeve was inserted into the fuel-air preparation zone (fig. 1). This sleeve extended from the fuel injectors to the flame holders and was

supported by radial struts. Two control sleeves were employed, one $14\frac{1}{2}$ inches in diameter for a fuel injector at the midposition of the diffuser annulus and the other $11\frac{1}{2}$ inches in diameter for the fuel-injector position near the centerbody wall. The fuel injectors were positioned midway between the control sleeve and the centerbody wall.

Fuel-air sampling. - The fuel-air profile upstream of the flame holder was established at a point 18 inches downstream of the fuel injectors. The profile was determined by withdrawing samples through a movable probe and then analyzing the mixture in an NACA Mixture Analyzer of the type reported in reference 5. The sampling probe was directed into the air stream and representative samples were obtained by withdrawing the mixture at approximately stream velocity. The probe consisted of a 1/8-inch-diameter tube with an orifice on the sampling end. Fuel-air samples were taken through the center line of one of the fuel spray nozzles.

PROCEDURE

Operating conditions. - The ram-jet combustor was operated over the following inlet conditions:

Inlet air static pressures, in. Hg abs	33 to 37
Inlet air temperature, °F.	600
Inlet air velocities, ft/sec	210 to 240

These values correspond to the combustor-inlet conditions in a ram-jet engine flying at a Mach number of 2.9 at an approximate altitude of 67,000 feet, with a diffuser pressure recovery of 70 percent.

Stability limits. - Lean stability data were taken at three radial positions of the fuel injector for each of the three flame-holder configurations tested. These fuel injection radii were 4.69, 5.69, and 6.69 inches. Engine blow-out was obtained for each combination of flame holder and injector by reducing fuel flow until no rise in air temperature was observed across the engine. Combustion was maintained in the engine pilot throughout all of the blow-out tests and the engine air mass flow was held constant.

The engine was operated over a fuel-air ratio range of lean blow-out to a maximum of 0.052 with the fuel injectors at the midposition and at the outer wall. Because of a serious fuel leakage which accompanied injection near the centerbody, the maximum fuel-air ratio attainable with the third fuel injector position was 0.037.

Combustion efficiency. - Combustion temperatures were determined by a heat-balance system similar to the method outlined in reference 6. At a given engine operating condition, the quench water flow was adjusted to a value insuring complete vaporization of the water. The water mass flow was varied so that an average outlet temperature of 900°F was maintained at the thermocouple station. The total enthalpy change of the fuel, air, quench water, and engine cooling water was divided by the input energy of the fuel to obtain combustion efficiency. Thermodynamic properties of the air, fuel, and water were obtained from references 7 and 8.

Fuel-air distribution. - Fuel-air samples were taken at a station immediately upstream of the flame holders. Samples were taken at an over-all fuel-air ratio of 0.035 for each flame-holder configuration, and for conditions of burning and nonburning in the combustor. Samples were not taken when the fuel control sleeve was in place. The fuel-air survey was made from the outer wall of the ram-jet engine to the inner wall formed by the centerbody.

The combustor-inlet pressure fluctuations were continuously recorded for all burning and nonburning conditions. Pressure traces were taken with each flame holder and for each fuel-injector position.

RESULTS AND DISCUSSION

Combustion efficiency. - A comparison of the combustion-efficiency data obtained with the three flame holders, each with the fuel injector at the same position, without the aid of the fuel control sleeve, is shown in figure 4. At a fuel-air ratio greater than 0.03, combustion efficiency was 90 to 100 percent. Flame-holder geometry had little effect on the combustion efficiency or lean blow-out limits of the engine despite flame-holder blocked area variations from 37 to 54 percent. The uniformity in combustion efficiencies obtained with the three flame holders was apparently due to the 600°F inlet air temperatures and higher-than-atmospheric pressures at which the engine was operated. The drop in air temperature between the fuel injectors and flame holders indicated that fuel vaporization was substantially complete before reaching the flame holders.

Lean fuel-air ratio limit. - Radial fuel injector position had a small effect on the maximum combustion efficiency but had a pronounced effect on lean blow-out limits as seen in figure 5. The blow-out limits for configuration C, for example, were extended from a fuel-air ratio of 0.0275 with fuel injection near the outer wall to 0.011 with fuel injected near the inner wall.

In figure 5, the last efficiency data points on the curves, plotted just before blow-out, do not represent the lowest fuel-air ratios for stable combustion. Since the shape of the curve is unknown in the region between the lowest fuel-air ratio data point and blow-out, this portion of the curve is dashed and merely serves to connect the lean limit of combustion with the known curve. The lack of data points between blow-out and lean operation is due to the fact that the fixed-area nozzle water spray, designed to quench combustion at high rates of heat release, did not quench effectively at fuel-air ratios lower than 0.017. This was partially due to the poor spray penetration at low water flow rates.

Fuel-air distribution. - The radial fuel-air distribution upstream of the flame holder is plotted as a percentage of the maximum fuel-air ratio in figure 6. Data for each configuration were taken at an over-all fuel-air ratio of 0.035 and with the fuel injector at the midposition between the outer and inner wall. For all configurations tested, the maximum fuel-air ratio occurred at the same radial distance from the pilot wall. However, figure 6 shows some variation in the fuel-air profiles for the three flame holders investigated. The most significant differences existed between the burning and nonburning conditions.

Data from figure 6 are replotted in figure 7 to a different scale. The abscissa in this figure is the square of the radial distance between the point of maximum fuel-air ratio and each sampling point. It is shown in reference 4 that for a point source of fuel injection into a continuous air stream the rate of spreading of fuel is proportional to the concentration gradient

$$\frac{\partial V}{\partial t} = - DA \frac{\partial f}{\partial R} \quad (1)$$

where

- V volume of gases diffusing past given boundary of area A
- t time
- D diffusion coefficient
- A area perpendicular to direction of diffusion
- f fuel-air ratio
- R distance in direction of diffusion

The following assumptions were made in order to reduce equation (1) to a practical and useful form:

- (1) Steady flow in system
- (2) Flat gas velocity profile
- (3) Amount of mixing in direction of flow X negligible in comparison with mixing in radial direction R
- (4) Diffusion coefficient D constant at all points in system
- (5) Duct very large in diameter

Applying the preceding assumptions and a material balance to the system, equation (1) becomes (reference 4)

$$f = \frac{W_f u}{4\pi W_a D X} e^{-\frac{u R^2}{4 D X}} \quad (2)$$

where

f fuel-air ratio at radius R and distance X downstream of injection point

W_f pounds of fuel injected per second, lb/sec

u air-stream velocity, ft/sec

W_a pounds of air per second passing a unit area in duct, lb/(sec)(sq ft)

D diffusion coefficient, sq ft/sec

X axial distance from fuel-injection point, ft

R radial distance from the maximum fuel-air ratio point, ft

Two theoretical fuel-air ratio distribution curves described by equation (2) are shown in figure 7. Both are plotted with values of diffusion coefficient which were chosen to fit the theoretical curves to the experimental data. These curves were graphically corrected for wall effects by the method given in reference 4.

Figure 7 includes only the data obtained in the region between the outer wall and the radius where peak fuel-air ratio was measured. The fuel-air distribution data in the region between the pilot cone and the

peak fuel-air ratio radius did not show a consistent trend. This was probably due to the interaction of adjacent fuel sprays which made the assumption of single-point injection invalid. However, since the rate of diffusion of fuel from the injection point into the region near the outer shell where the mixture was too lean for combustion was of primary interest, the lack of consistency in the inner zone distribution was not investigated further.

The diffusion coefficient, for the case of burning in the engine, was approximately 1.6 square feet per second, whereas the diffusion coefficient for the nonburning case was approximately 0.6 square foot per second. The diffusion coefficient is seen to be two to three times as high for the burning condition as for the isothermal.

Pressure pulsations. - The amplitude and frequency of pressure pulsations at the combustor inlet, with burning, for the various flame-holder configurations are shown in figure 8. The nonburning case with configuration C only is shown in figure 8(a). Engine frequencies can be compared with a 60 cycle per second standard included in figure 8(a). For these tests, in which the pressure fluctuations were comparable, the fuel-air distribution curves (fig. 6) show the mixing rate to be proportional to the amplitude of the pressure pulsations. The amplitude of the pressure pulsations without burning was approximately 0.1 pound per square inch. With combustion the amplitude increased considerably. The maximum value was 0.3 pound per square inch with configurations A and B and 0.2 pound per square inch with configuration C.

A possible factor contributing to the greater spreading of fuel with combustion present is the greater radial penetration of the conical fuel sprays under the influence of the pulsations induced by the combustion. Whatever the mechanism causing the fuel to spread, the effect can be described by the diffusion equation (2).

Mechanical control of fuel-air distribution. - It was apparent from data such as those in figure 7 that judicious selection of fuel-injector location was not sufficient to insure the fuel-air distribution required for efficient operation at lean fuel-air ratios. Fuel-injector positions providing an optimum fuel-air pattern under one condition of burning would prove unsatisfactory under new conditions because of the change in amplitude and frequency of pressure pulsations. More positive control of mixing was necessary to insure the stoichiometric fuel-air mixture required at the pilot for efficient operation. A cylindrical sleeve, therefore, was inserted into the fuel preparation zone which physically limited the spreading of the fuel. The extension of the engine stability limits with controlled mixing is shown in figure 9. Improved stability limits for injection at the centerbody are shown in figure 9. The lean fuel-air ratio limit for the engine was extended from 0.0115 without the control sleeve to 0.007 with the aid of the sleeve. Figure 9 also shows the effect of controlled mixing on stability limits for the injectors at the midposition. The blow-out limit again was extended, from fuel-air ratios of 0.0235 to 0.0185.

The crossing-over of efficiency curves at a fuel-air ratio of 0.029 for the centerbody fuel injection and at 0.035 for the midposition fuel injectors indicates a stoichiometric condition at the pilot. To operate far above these fuel-air ratios, it would be necessary to introduce the additional fuel into the outer regions of the flame holder.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of combustion on diffusion in the fuel preparation zone of a 16-inch ram-jet engine:

1. Under realistic ram-jet engine flight conditions, where the combustor inlet pressure was approximately atmospheric and the inlet temperature 600°F , variation in the flame-holder geometry had little effect on the combustion efficiency or the lean blow-out limits. At a fuel-air ratio greater than 0.03, combustion efficiency was 90 to 100 percent.

2. Variation in the fuel distribution had a significant effect on the lean limit and little effect on the maximum combustion efficiency.

3. The fuel-air distribution in the mixing zone upstream of the flame holder was found to be a function of the amplitude of the combustor-inlet pressure pulsations. The largest eddy diffusion coefficient occurred at the maximum combustor-inlet pressure fluctuations. The diffusion coefficient varied from 0.6 square foot per second for nonburning to 1.6 square feet per second with burning.

4. A simple mechanical method of limiting the fuel-air mixing was employed to extend the lean combustion limit of operation to a fuel-air ratio of 0.007.

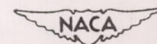
Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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8. Keenan, Joseph H., and Keyes, Frederick G.: Thermodynamic Properties of Steam. John Wiley & Sons, Inc., 1936.

TABLE I - SPECIFICATIONS AND ANALYSIS OF PRIMARY ENGINE

FUEL MIL-F-5624 GRADE JP-3



	Specifications MIL-F-5624	Analysis MIL-F-5624 (NACA fuel 51-21)
A.S.T.M. distillation		
D86-46 (°F)		
Initial boiling point		116
Percentage evaporated		
5		155
10		176
20		206
30		230
40		251
50		274
60		299
70		333
80		370
90	400 (min.)	416
Final boiling point	600 (max.)	485
Residue (percent)	1.5 (max.)	1.0
Loss (percent)	1.5 (max.)	1.0
Aromatics (percent by volume) A.S.T.M.		
D875-46T	25 (max.)	19
Specific gravity	0.728 to 0.802	0.749
Reid vapor pressure (lb/sq in.)	5 to 7	5.8
Hydrogen-carbon ratio	-----	0.173
Net heat of combustion (Btu/lb)	18,400 (min.)	18,640

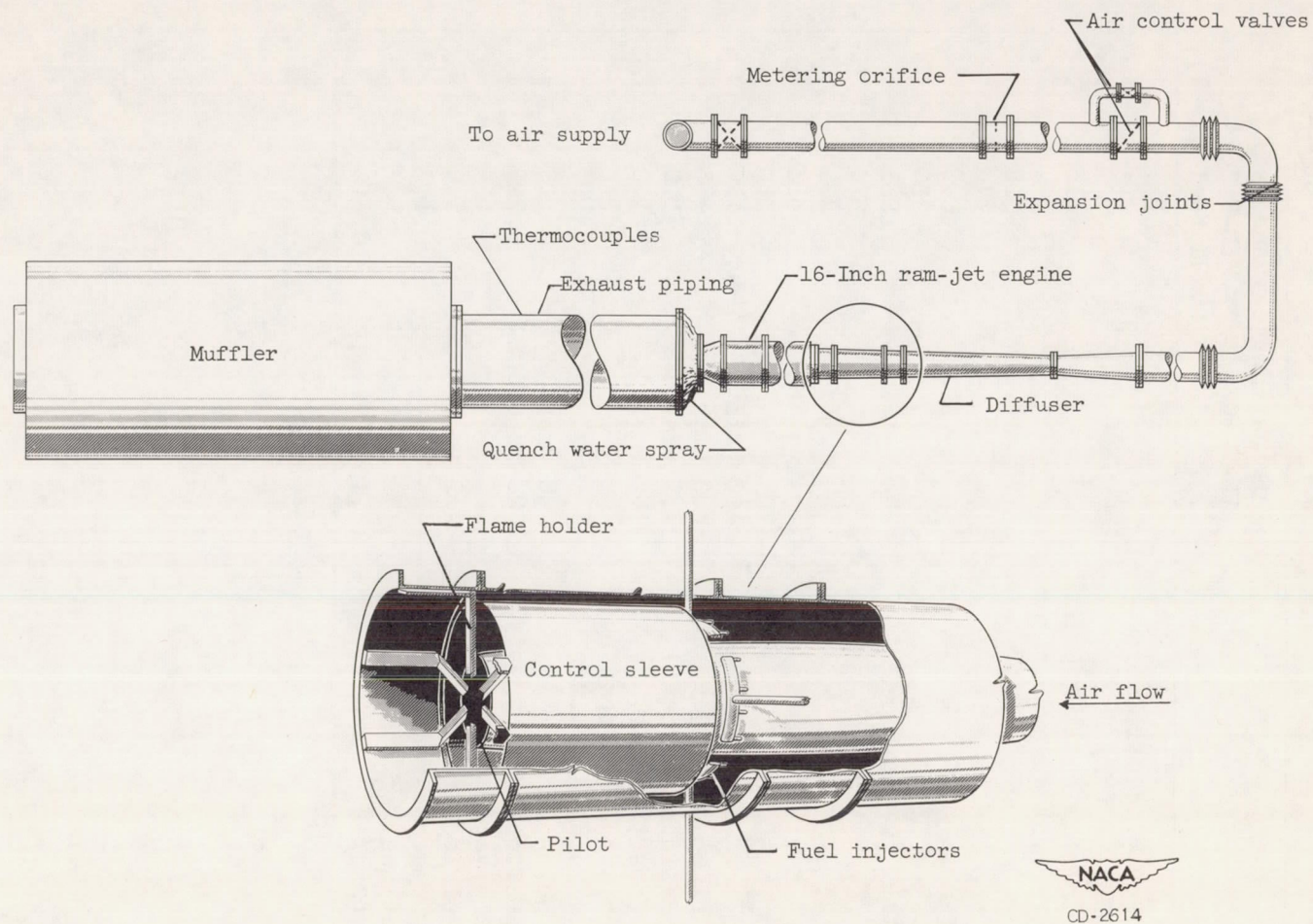


Figure 1. - Installation of 16-inch ram-jet engine.

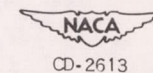
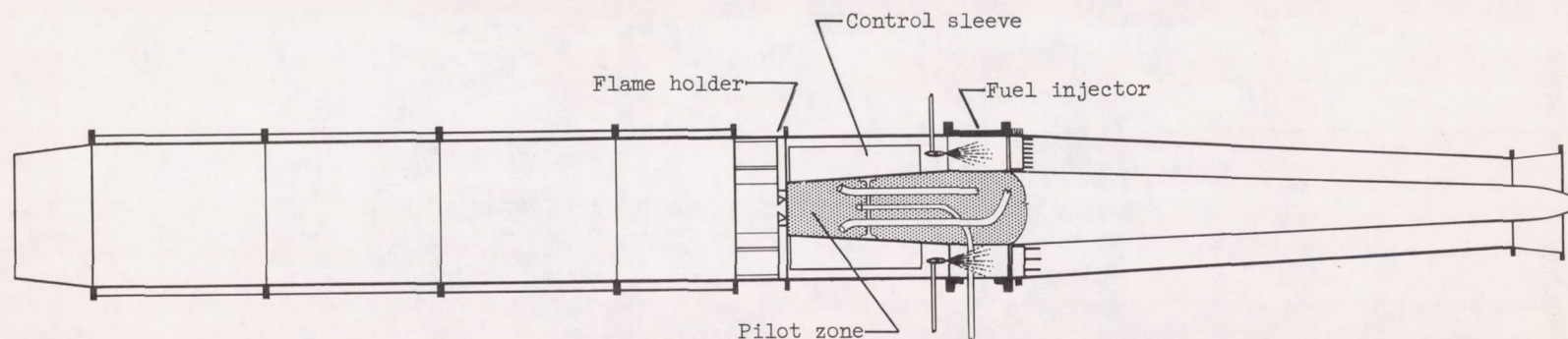
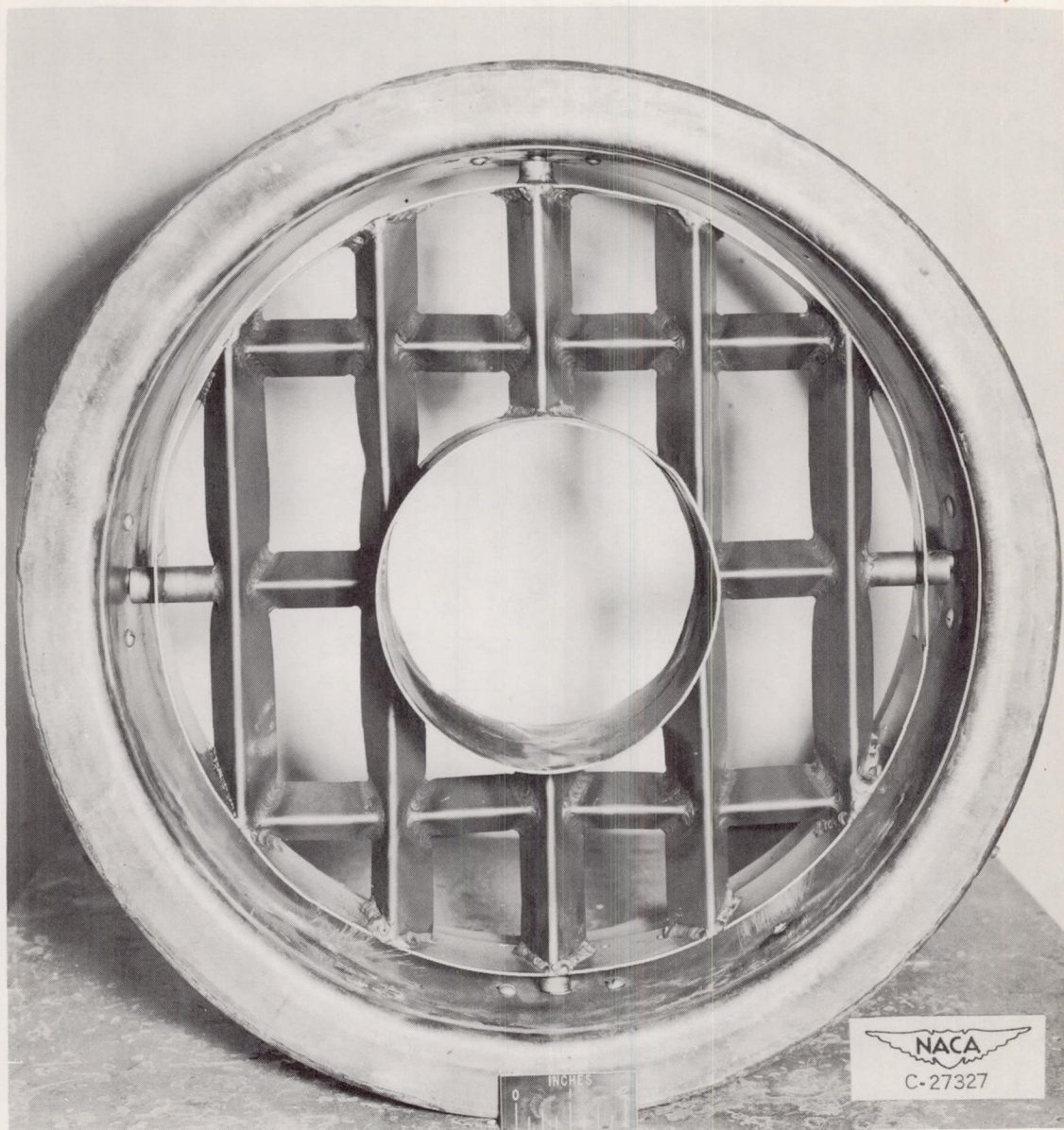
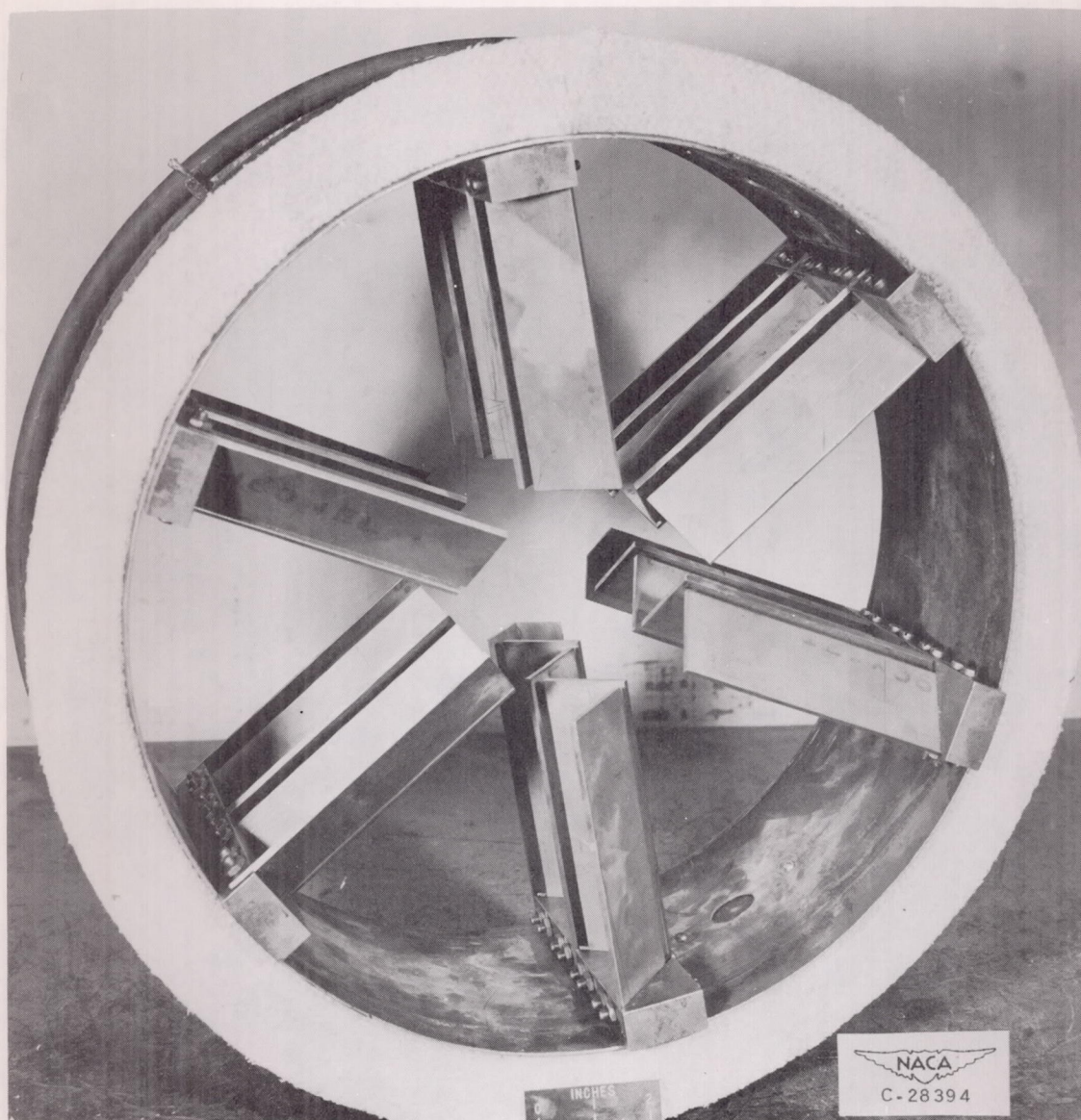


Figure 2. - Sketch of 16-inch ram-jet engine showing position of fuel injector, flame holder, and mixing control sleeve.



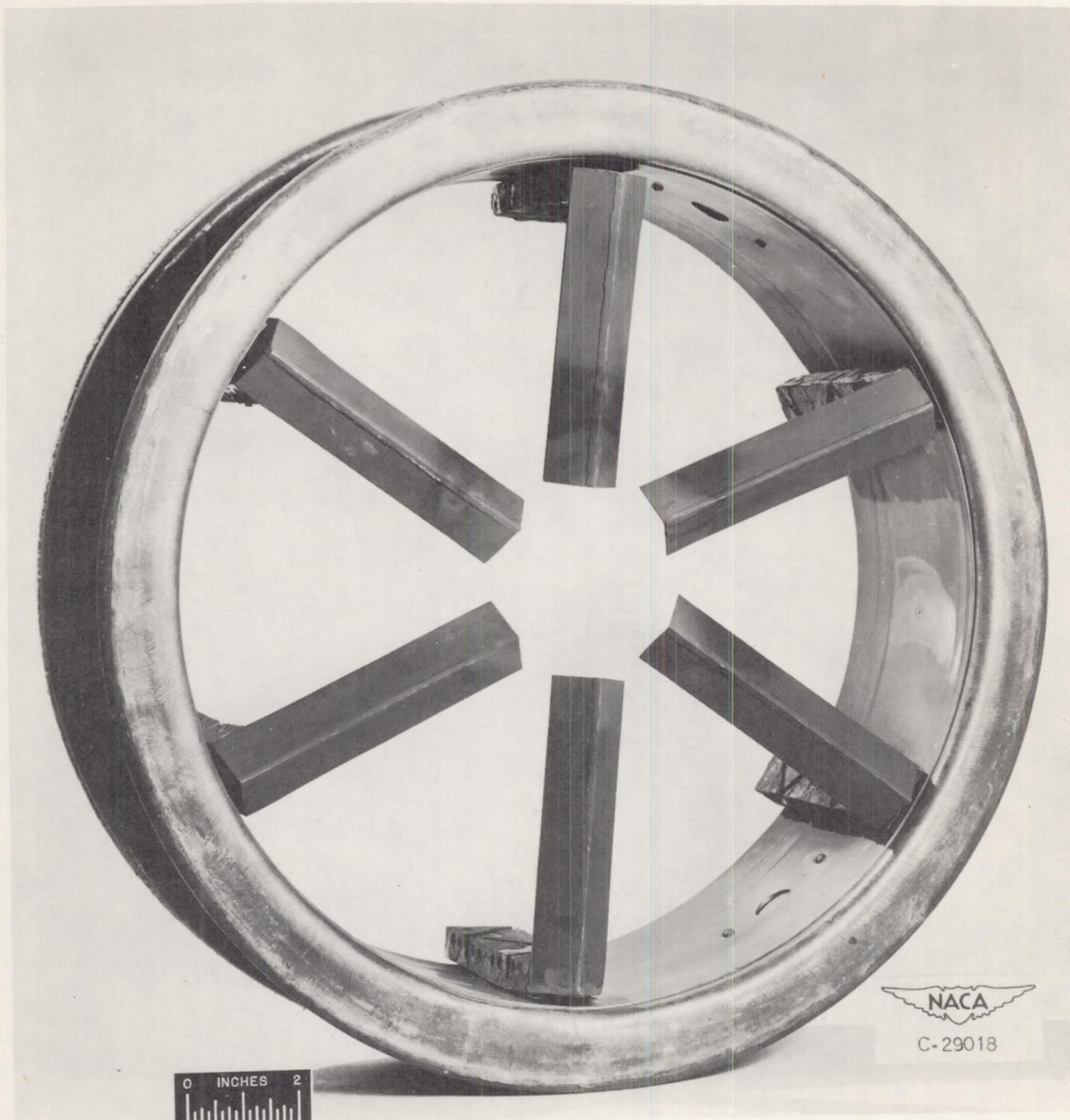
(a) Configuration A showing cross V-gutters, upstream face.

Figure 3. - Flame-holder configurations.



(b) Configuration B showing immersed surfaces, downstream face.

Figure 3. - Continued. Flame-holder configurations.



(c) Configuration C showing radial V-gutters, upstream face.

Figure 3. - Concluded. Flame-holder configurations.

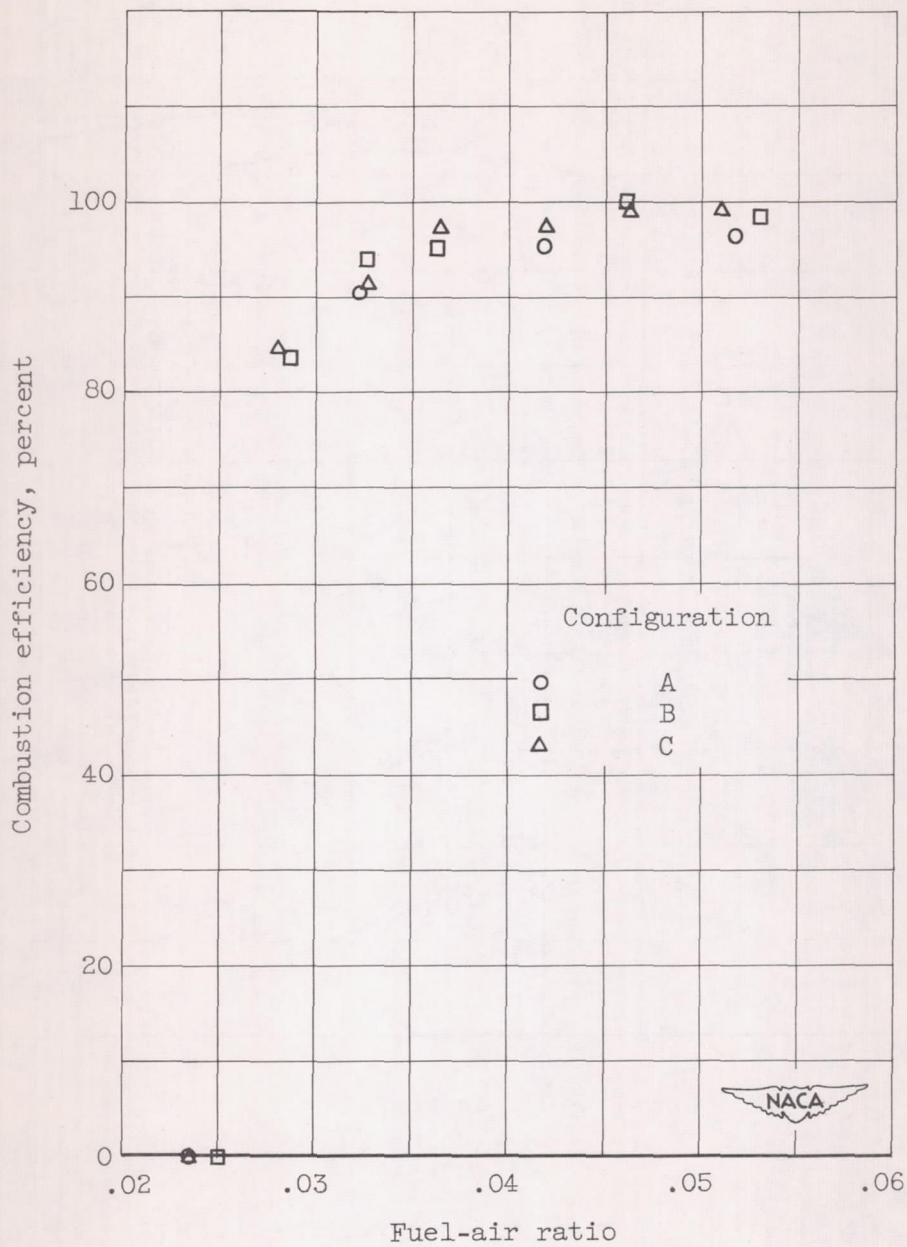
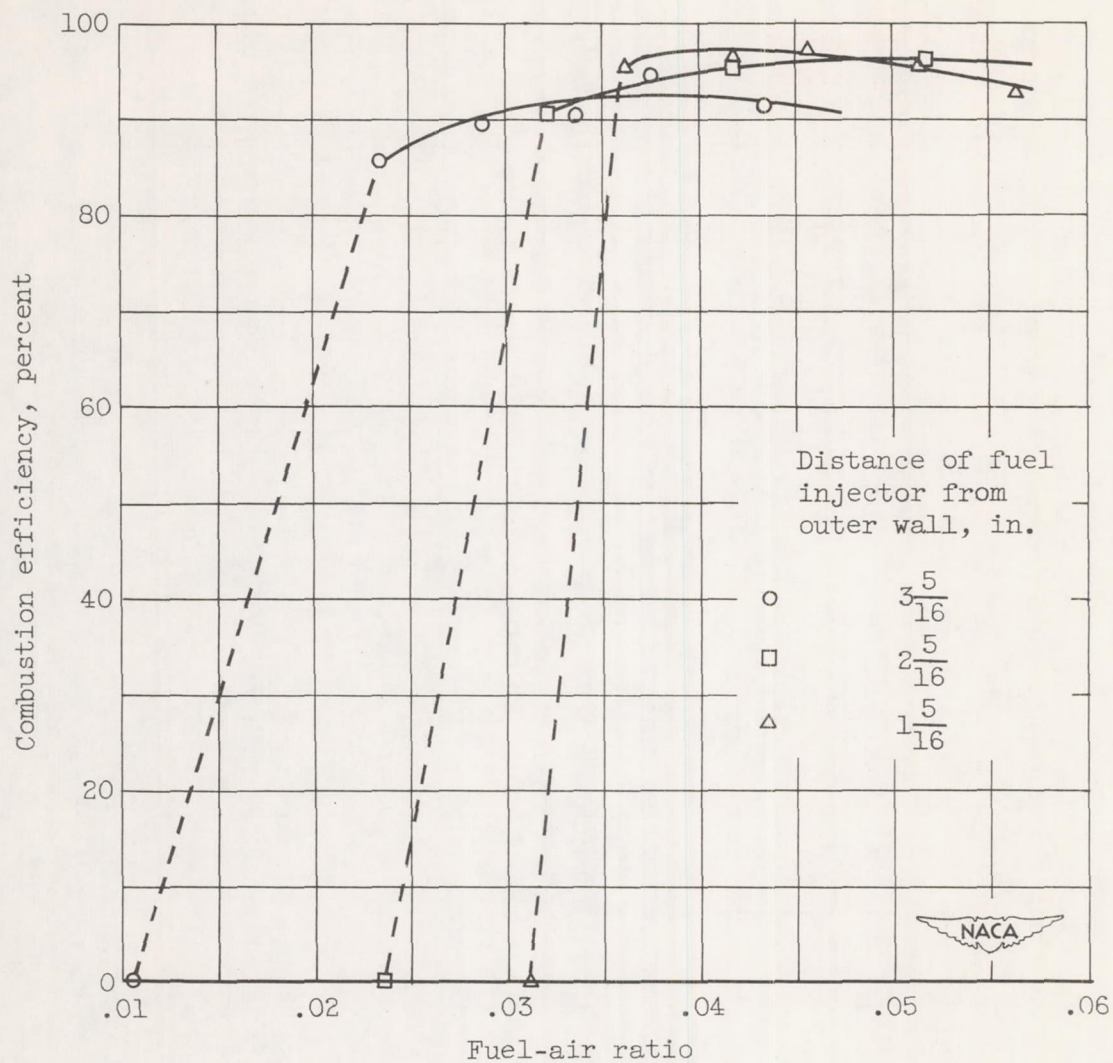
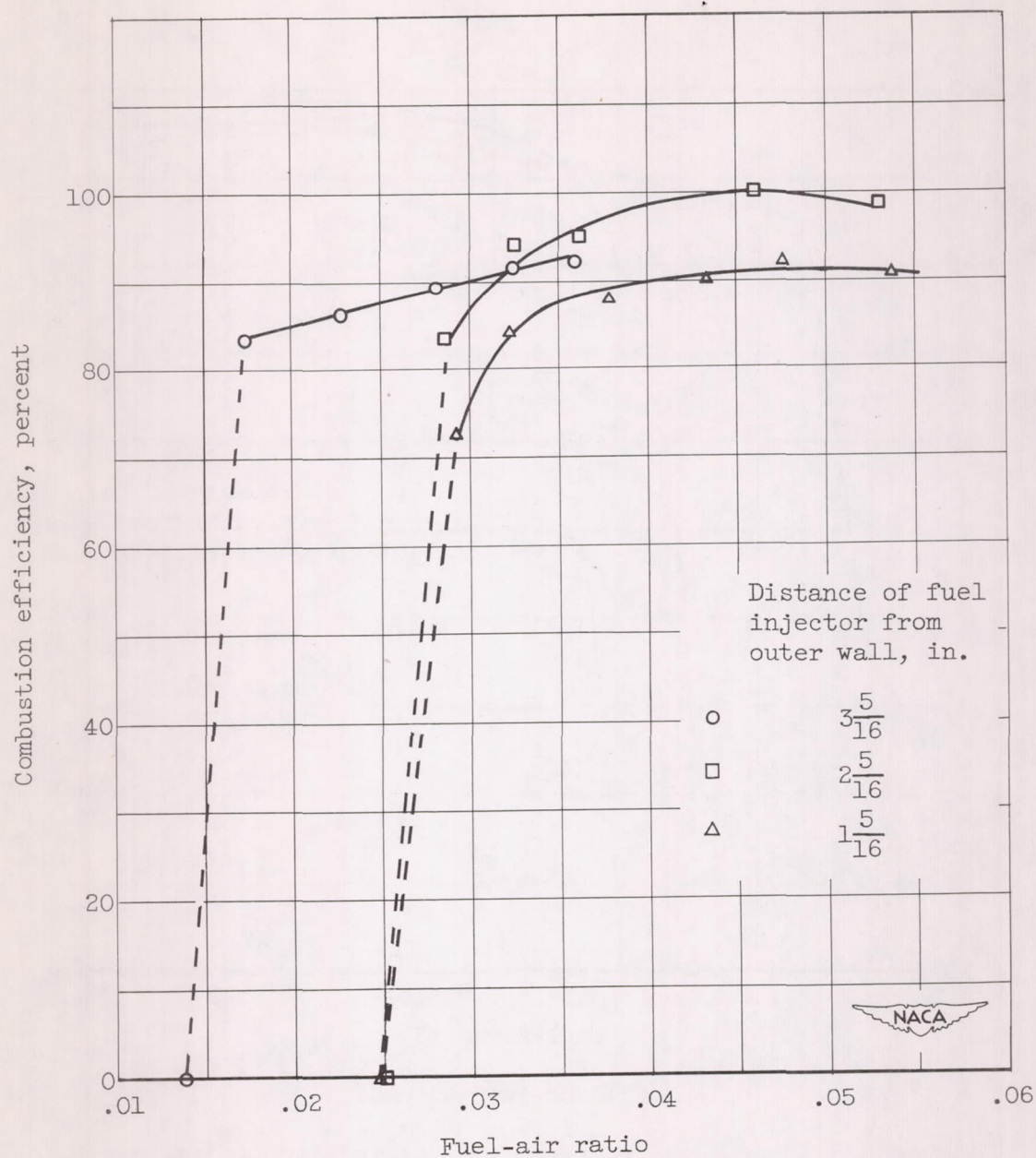


Figure 4. - Effect of fuel-air ratio and flame-holder geometry on combustor performance. Fuel injectors $2\frac{5}{16}$ inches from outer wall.



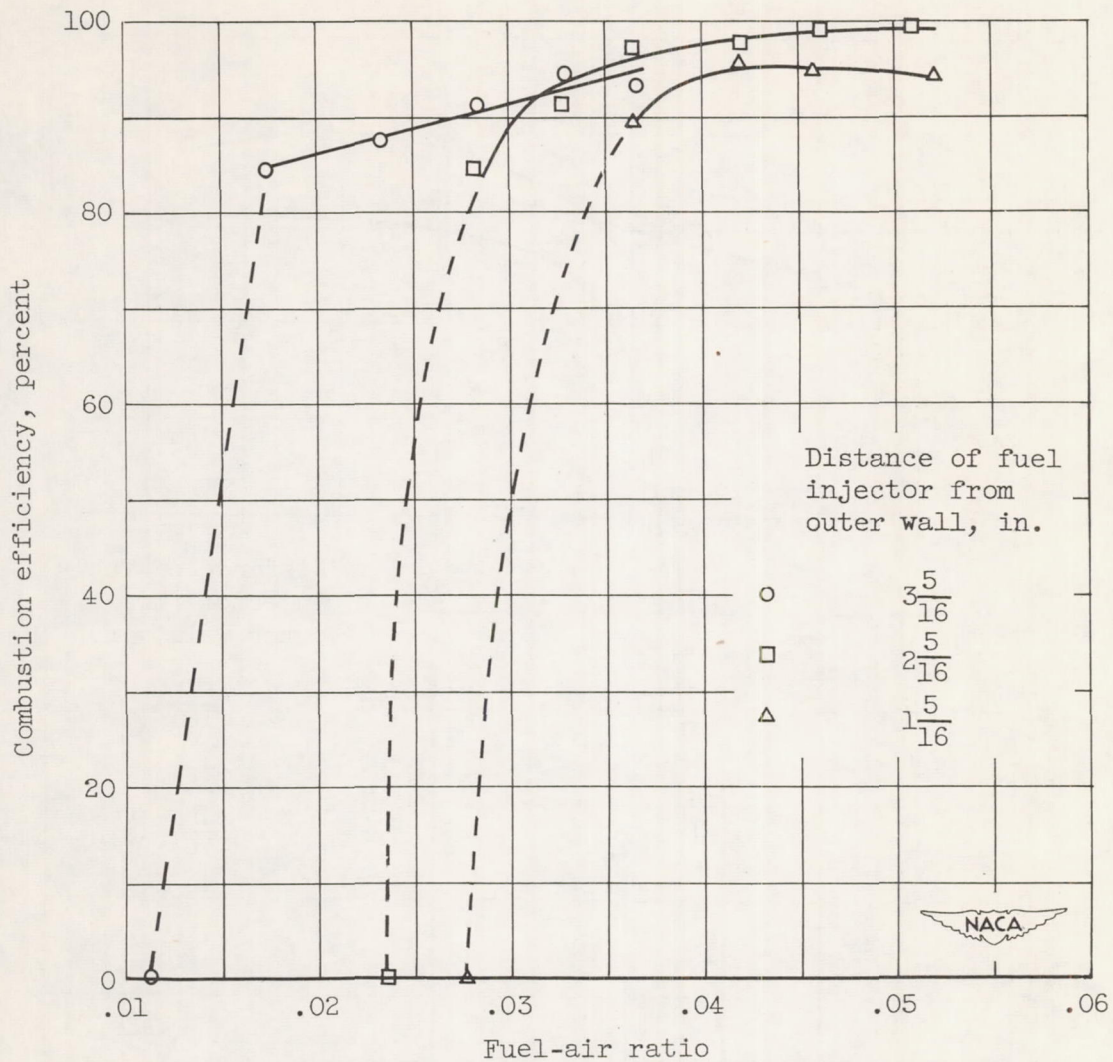
(a) Configuration A.

Figure 5. - Effect of fuel-injector radial position on combustor performance.



(b) Configuration B.

Figure 5. - Continued. Effect of fuel-injector radial position on combustor performance.



(c) Configuration C.

Figure 5. - Concluded. Effect of fuel-injector radial position on combustor performance.

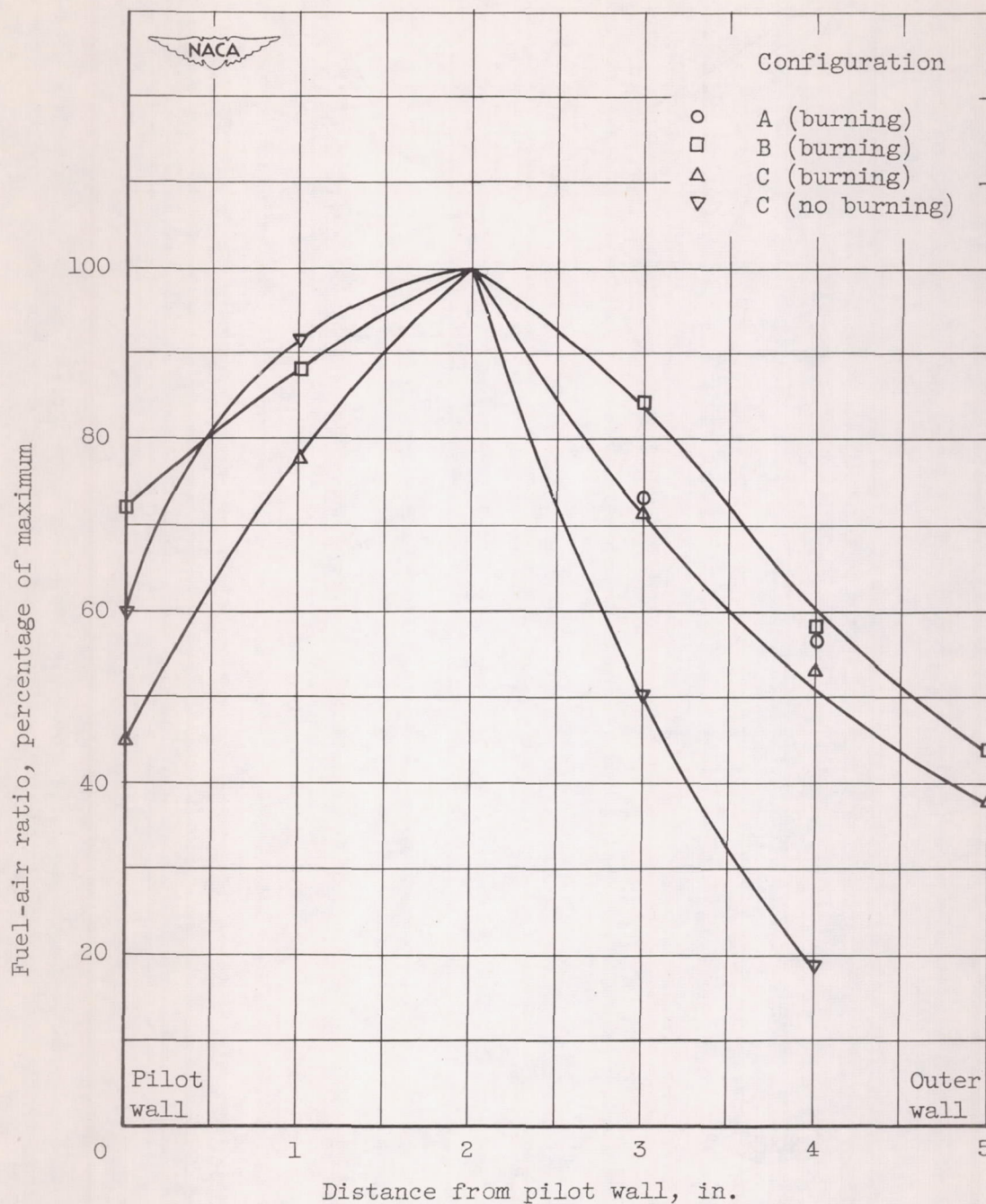


Figure 6. - Fuel-air ratio distribution upstream of flame holder with burning (fuel-air ratio, 0.035) and with no burning.

Fuel injector $2\frac{5}{16}$ inches from outer wall.

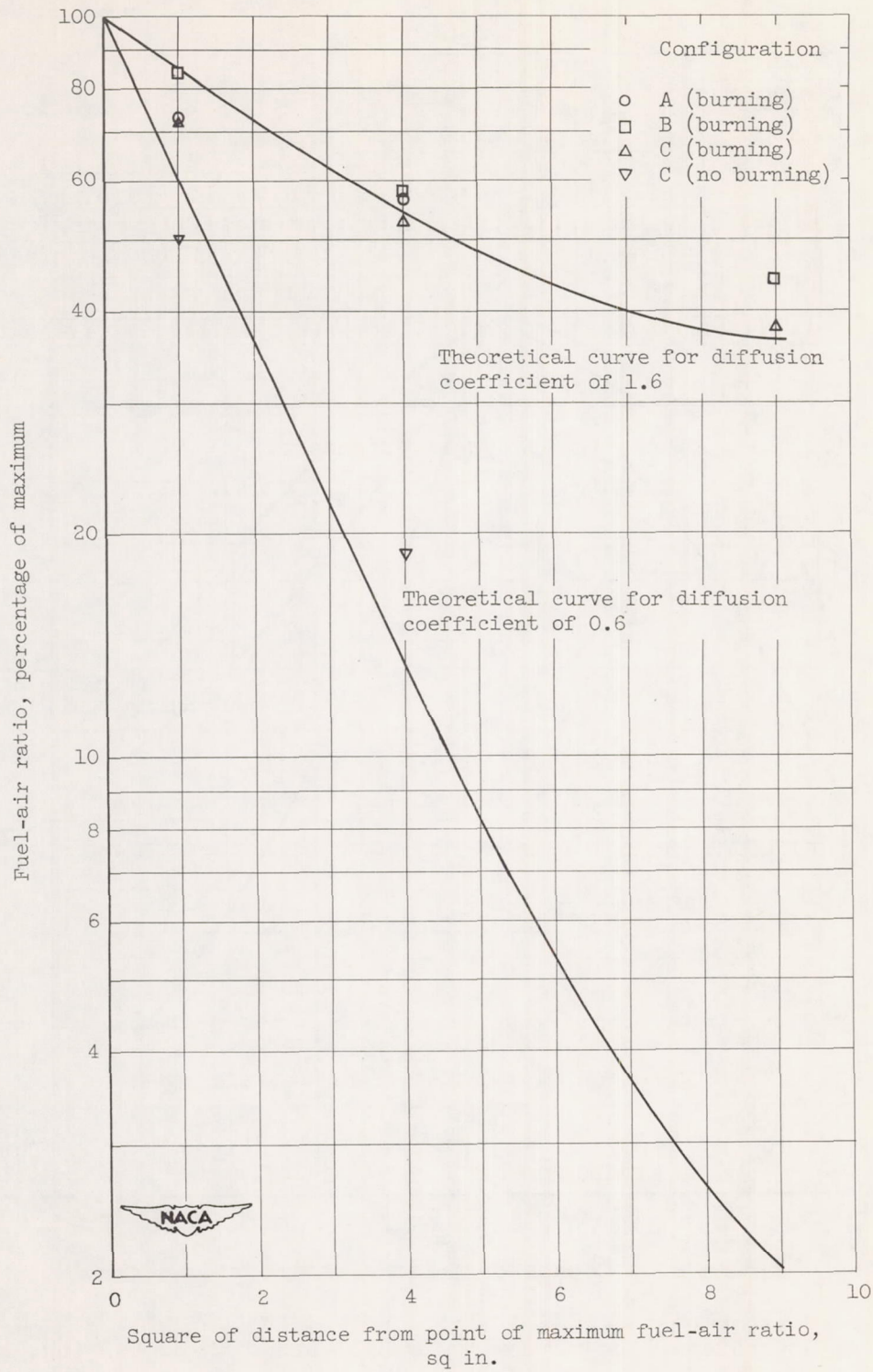
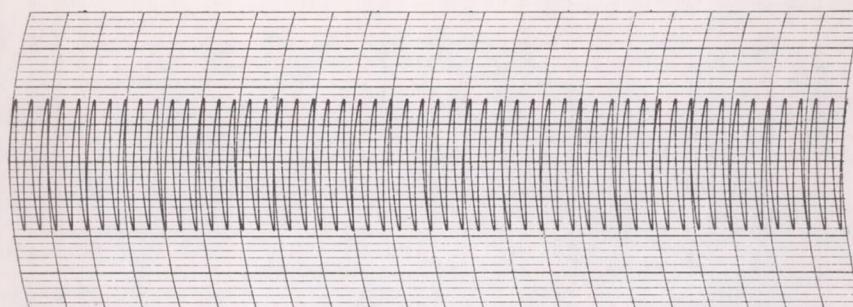
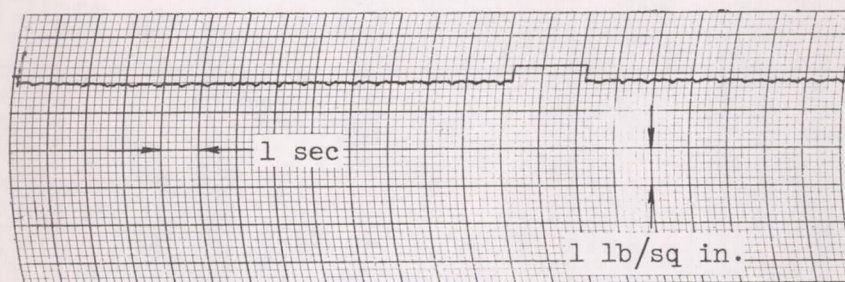


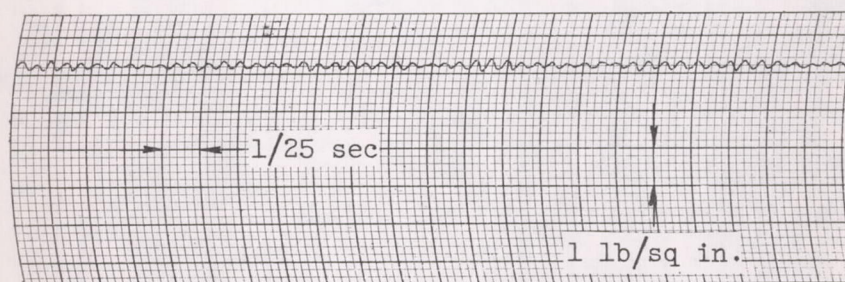
Figure 7. - Fuel-air diffusion coefficient upstream of flame holder with burning (fuel-air ratio, 0.035) and with no burning.



60 cycles/sec standard.



Configuration C; no burning.



Configuration C; burning with fuel-air ratio
of 0.035.

(a) Configuration C showing influence
of burning.

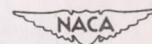
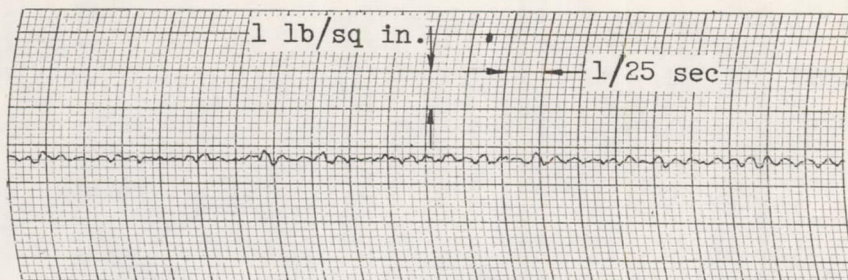
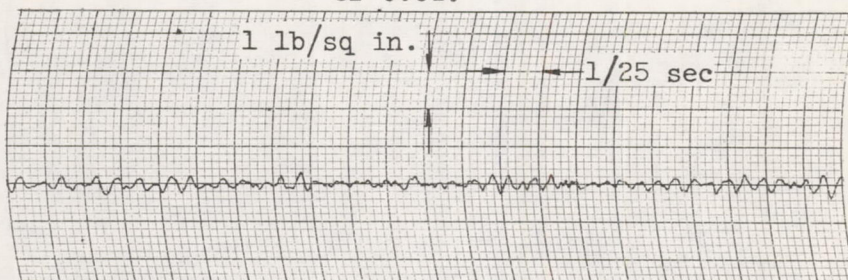


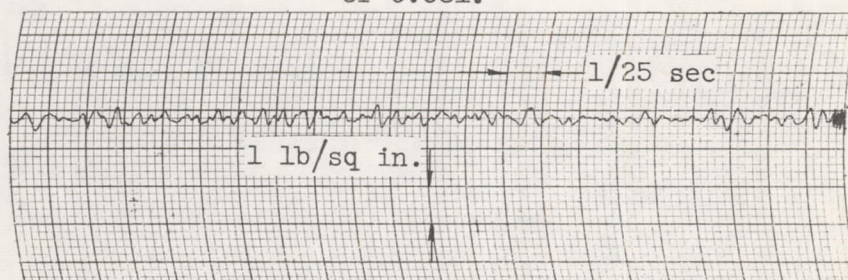
Figure 8. - Combustor inlet pressure pulsations.



Configuration A; burning with fuel-air ratio of 0.04.



Configuration A; burning with fuel-air ratio of 0.031.



Configuration B; burning with fuel-air ratio of 0.035.

(b) Configurations A and B.

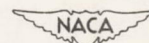


Figure 8. - Concluded. Combustor inlet pressure pulsations.

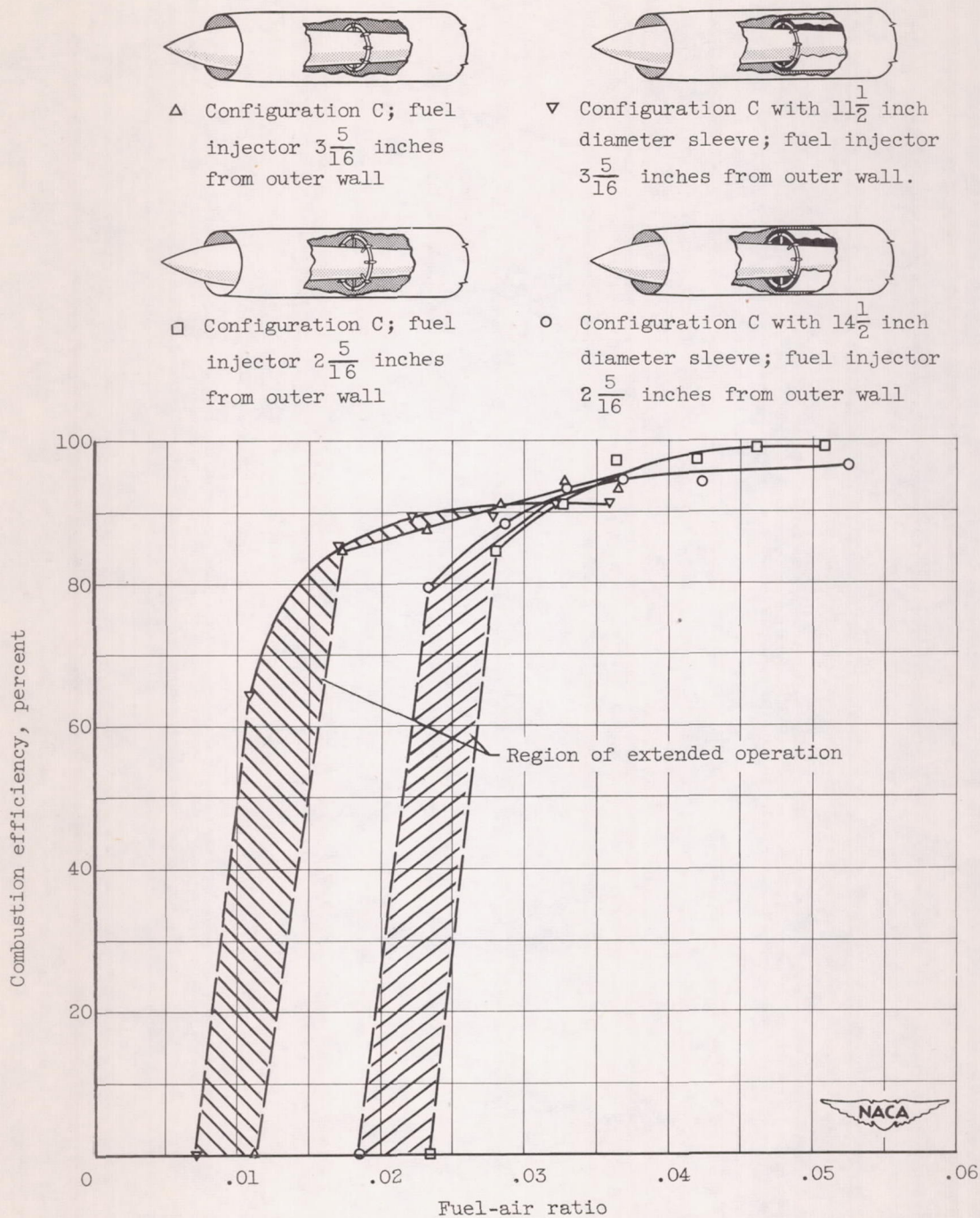


Figure 9. - Extension of operating range by control of fuel-air mixing.

